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SPACE DEBRIS RESEARCH PHASE ONE PROGRAM: ABSTRACTS FROM PUBLISHED PAPERS (1990-1993)

Compiled by
Scott R. Maethner

June 1994

Final Report

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PHILLIPS LABORATORY
Advanced Weapons and Survivability Directorate
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This final report was prepared by the Phillips Laboratory, Kirtland Air Force Base, New Mexico, under Job Order AFOTEC03. Major Albert E. Reinhardt (WSC) was the Phillips Laboratory Space Debris Program Manager. First Lieutenant Scott R. Maethner (WSC) was the Phillips Laboratory Project Officer-in-Charge.

This technical report has been reviewed and is approved for publication.

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13. ABSTRACT *(Maximum 200 words)*

This document contains the abstracts from 63 papers published in support of the U.S. Air Force Phillips Laboratory Phase One Space Debris Research Program. This program, which was completed on 31 Dec 93, focused on characterizing the low earth orbit space debris environment and establishing the current and projected hazards to U.S. Air Force and Department of Defense space assets. The program emphasized both the measurement and modeling efforts needed to characterize the current debris environment for debris sizes down to 1 mm. In addition to the paper abstracts, this document lists paper titles, authors, and the paper publication sources.

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1.0 DEBRIS MEASUREMENTS

"Debris Correlation Using the Rockwell Worldview Simulation System"
M.F. Abernathy, J. Houchard, M.G. Puccetti, and J.V. Lambert
Rockwell International
1993 MIT Lincoln Laboratory Space Surveillance Workshop Proceedings, Project Report STK-206, Vol. I, March 1993

This paper describes the use of a sky simulation tool to facilitate the tracking and categorization of candidate debris objects. One of the problems in cataloging space debris is separating it from the myriad of non-debris objects visible to observatories. In addition to the distraction of celestial bodies, some several thousand objects orbit the planet. This paper describes how the sky simulator (Rockwell WorldView) is used to provide a video overlay to assist human operators in correlating known versus unknown space objects (debris). The methods employed in developing the simulator are described, along with validation procedures. We will present a video showing the system in operation producing correlation overlays in real time.

"Orbital Debris Environment: An Update"
P. Dao
32nd Aerospace Sciences Meeting, AIAA-94-0592, 10 January 1994

To properly assess the space debris environment and model the risk posed by collisions between space assets and man-made space debris, new sources of data have been planned and recently obtained. Critical measurements of the population to cm sizes are being made by the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) in this area lacking in data. Two questions to be answered by these efforts are: what is the size of the debris population and how does it impact the operational and planned space programs. The number of small sized debris obviously needed quantification because it is expected to contribute the most to the total population of space objects in Earth orbits. The Air Force Phillips Laboratory (PL) is undertaking a concerted effort to assess the debris environment by optical measurement and modeling. Debris measurements with optical telescopes operated by the MIT/Lincoln Laboratory in Socorro, New Mexico, and the PL Laser and Imaging Directorate, in Maui, Hawaii, and the NASA-sponsored debris Haystack radar have resulted in new data on observed detection rates, and measured or estimated eccentricity, semi-major axis and inclination distributions. In this paper, the problem of collisions is studied as a statistical assessment and the hazard will be reported as a probability of collision or collision rate. Expectations of detection rate are computed for each debris observing session and compared with actual rates. Differences in rate are used to update the size of the population. From the updated number of objects and listing of their fundamental orbital parameters, one can compute spatial density and collision flux. A collision flux model is then used to compute the flux associated with a spacecraft in a 28 degree inclination and 500 km altitude orbit. Results will be compared with NASA reported values of flux for radar sensitive objects.

"Space Debris Measurements and Modeling"

P. Dao and R. McNutt

AAS Astrodynamics Specialist Conference Proceedings, AAS 91-371, August 1991

The most serious difficulties in modeling the evolution of the debris environment have been the lack of debris data in the size range from 0.1 to 10 cm to completely define the current environment and the understanding of the breakup initial conditions which govern the propagation of fragments. A space debris measurement and modeling effort is undertaken at the Phillips Laboratory (PL) to mitigate these deficiencies. The approach is to quantify debris population with sensors capable of detecting debris of smaller sizes and develop a model designed for facile coupling with the acquired data. A review of the modeling effort is given in this paper with emphasis placed on the breakup initial state vectors and atmospheric decay.

"Space Debris Optical Measurement: Use of Stare Sensors"

P. Dao, A. Wilson, and A.E. Reinhardt

31st Annual Aerospace Sciences Meeting, AIAA-93-159, 16 January 1993

To quantitatively assess the space debris environment and its impact on current and future space programs, the U.S. Air Force Phillips Lab (PL) has organized a measurement program to characterize the environment using existing optical telescope facilities. These facilities include the Maui AMOS site operated by the PL/Laser and Imaging Directorate and the Socorro, New Mexico, site, operated by MIT/Lincoln Laboratory. The main objective is to define the baseline collisional flux in orbit. There are two competing approaches. The first is fully deterministic and based on a complete catalog of tracked objects similar to the satellite catalog maintained by Space Command. The second approach relies on a *statistical* representation of the debris/object population consisting of incomplete or less well defined orbital element sets. For the latter, stare sensors could be used to provide data. As an example, one could park a telescope at fixed orientation or in a sidereal slew mode to detect debris/objects crossing the field of view (FOV). Object inclination and altitude could be inferred from its motion in the FOV. In this mode of operation, referred to as *survey* or *stare*, one does not have a fully deterministic description of the orbit. However, the advantage is the ability to translate sparse observation results into quantitative measurement of the debris environment without having to maintain a full debris catalog. It has also been claimed by many that (1) an estimate of a space object's altitude could be inferred from its measured angular motion using the assumption that all orbits are circular; (2) the collision flux computed from approximated altitudes does not deviate substantially from the true value. This paper will assess the validity of the circular orbit assumption and approximation (COA). We will also attempt to evaluate the effects of sensor sensitivity on the sampling of the debris population. Average systematic bias and uncertainty are also obtained for the population represented by on-orbit satellite catalogs. We will also assess the effects of using COA to estimate debris population and flux.

"Orbital Debris Characterization: ETS Staring Survey"
D.M. Gibson, E.C. Pearce, M.S. Blythe, and P.J. Trujillo
Space Debris Detection and Mitigation Proceedings, SPIE 1951, April 1993

As part of Air Force Phillips Laboratory's Space Debris Program, MIT Lincoln Laboratory's Experimental Test System has conducted three separate types of surveys to detect small uncataloged debris. In addition, follow-up metric and photometric observations have also been made. The goal of these observations is to characterize the low earth space debris environment down to sizes of 1 cm. The dual telescope staring survey, conducted in 1990, employed stereo (parallactic) viewing to enable estimates of the target altitudes to be determined. We will describe the stereo survey techniques, a pipeline image processor to reduce the video tapes, and our plans for data analyses. We will also present a brief overview of the program results to date, emphasizing extensive observations of two small optically detected debris.

"Detecting Small Debris Using a Ground-Based Photon Counting Detector"
C. Ho, W.C. Preidhorsky, and M.H. Baron
Space Debris Detection and Mitigation, Proceedings, SPIE 1951, April 1993

We describe a sensitive technique for detecting small space debris that exploits a fast photon-counting imager. Microchannel plate detectors using crossed delay-line readout can achieve a resolution of 2048×2048 spatial pixels and a maximum count rate of about 10^6 photons per second. A baseline debris-tracking system might couple this detector to a 16-cm aperture telescope. The detector yields x, y, and time information for each detected photon. When visualized in (x,y,t) space, photons from a fast-moving orbital object appear on a straight line. They can be distinguished from diffuse background photons, randomly scattered in the space, and star photons, which fall on a line with sidereal velocity. By searching for this unique signature, we can detect and track small debris objects. At dawn and dusk, a spherical object of 1.3 cm diameter at 400 km will reflect sunlight for an apparent magnitude of V $\approx$ 16. The baseline system should detect about 16 photons from this object as it crosses a 1 degree field of view in about 1 second. The line in (x,y,t) space will be significant in a diffuse background of $\sim 10^6$ photons. We discuss the data processing scheme and line detection algorithm. The advantages of this technique are that one can (1) detect cm-sized debris objects with a small telescope, and (2) detect debris moving with any direction and velocity. In this paper, we describe the progress in the development of a detector and data acquisition system, the preparation for a field test for such a system, and the development and optimization of the data analysis algorithm. Detection sensitivity would currently be constrained by the capability of the data acquisition and the data processing systems, but further improvements could alleviate these bottlenecks.

"Orbital Debris Correlation and Analysis at the Air Force Maui Optical Station (AMOS)"

R.K. Jessop, J.L. Africano, J.V. Lambert, R. Rappold, R.S. Medrano, P.W. Kervin, and K.E. Kissell

1993 MIT Lincoln Laboratory Space Surveillance Workshop Proceedings, Project Report STK-206, Vol. I, March 1993

The Air Force Maui Optical Station (AMOS) is conducting searches, measurements, and analyses of orbital debris for the Air Force Phillips Laboratory and Air Force Space Command in support of the Air Force Orbital Debris Measurement Program. Algorithms and software have been developed for correlation of objects observed on GEODSS video with the Space Command satellite catalogue and with previously observed but uncorrelated objects. The developed algorithms apply gross and fine filters to reduce the number of candidate catalogued objects from further consideration. The software uses and object-oriented approach that closely models the problem/analysis domain and performs analysis verification both at compile time and during run time. Techniques have also been developed for determining the magnitude or brightness of both correlated and uncorrelated objects using calibration star fields. From the identified (correlated) objects, plots of radar cross section (RCS) versus normalized magnitude are produced. A size may then be assigned to the debris objects assuming that the optical properties of these objects are similar to the optical properties of the correlated objects.

"Air Force Maui Optical Station (AMOS) Orbital Debris Detection Program"

P.W. Kervin, S.D. Kuo, R.S. Medrano, D.L. Covey, S.D. Baker, J.L. Africano, J.V. Lambert, and K.E. Kissell

First European Conference on Space Debris, Proceedings, ESA SD-01, Darmstadt, Germany, April 1993

The United States Air Force Phillips Laboratory has been conducting nightly observations of the debris environment using the Air Force Maui Optical Station (AMOS) and the Ground-based Electro-Optical Space Surveillance (GEODSS) facilities, both of which are located at the Maui Space Surveillance Site, collecting approximately fifty to sixty hours of observation per month during twilight periods. The goals of this program will be discussed, with emphasis on the detection program. This includes discussion of telescopes and sensors available, how they are used, choice of telescope, and mode of operation. Also discussed will be the data collected, and the correlation of our detections with our local catalog of space objects. Analysis is presented for observations taken during the last two years, both at the Maui site as well as the Diego Garcia GEODSS site.

"Optical Observations of the Orbital Debris Environment"

P.W. Kervin, J.L. Africano, S.D. Kuo, J.V. Lambert, R.S. Medrano, and K.E. Kissell

Space Debris Detection and Mitigation, Proceedings, SPIE 1951, April 1993

The Air Force Phillips Laboratory (PL) is tasked by Air Force Space Command to characterize the orbital debris environment. Part of this task is to search for and detect debris using the optical facilities at the PL Air Force Maui Optical Station (AMOS), which is located at the Maui Space Surveillance Site (MSSS). The goals of the program are discussed, with emphasis on the detection program. This includes telescopes and sensors available, how they are used, and handoffs from one sensor to another. Results of this correlation, as well as conclusions on the orbital debris environment, are presented.

"Orbital Debris Characterization Measurements at the Air Force Maui Optical Station (AMOS)"

P.W. Kervin, S.D. Kuo, R.S. Medrano, J.L. Africano, J.V. Lambert, and K.E. Kissell

1993 MIT Lincoln Laboratory Space Surveillance Workshop Proceedings, Project Report STK-206, Vol. II, March 1993

The Air Force Maui Optical Station (AMOS) is conducting searches, measurements, and analyses of orbital debris for Air Force Space Command and the Phillips Laboratory (PL) in support of the Air Force Orbital Debris Measurement program. The objective of this program is to detect orbiting objects not currently in the U.S. Space Command Space Surveillance Center (SSC) Catalog. Once detected, further objectives are to track, catalog, and maintain those objects locally, to determine statistics on detected objects, and perform relevant analyses. In addition to this surveillance activity, AMOS is also automating the detection and analysis process, and developing a prototype surveillance system for detection of orbital debris. The AMOS program is a joint effort between various government and contractor agencies to employ the wide field of view optical sensors at the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) site at the Maui Space Surveillance Site (MSSS) and narrow field of view tracking sensors at AMOS (which is also located at the MSSS).

"Real Time Orbit Determination of Orbital Space Debris"
S.D. Kuo
1993 MIT Lincoln Laboratory Space Surveillance Workshop Proceedings, Project Report STK-206, Vol. I, March 1993

The Air Force Maui Optical Station (AMOS) is currently cataloging pieces of space debris using the GEODSS 24 inch auxiliary telescope with a 6 degree field of view. A new method has been implemented that permits real time determination of the orbital element set of a previously uncataloged piece of debris. Using the Prototype AMOS Computer Control System (PACCS), two observation points are recorded when a piece of debris passes through the auxiliary telescope field of view. These two observation points are fit to a circular orbit and an estimated slant range is obtained. Using the range, the azimuth (az), and elevation (el) of the observation points, a state vector can be estimated. This vector is then propagated and fed into PACCS which then generates an orbital track for the Beam Director/Tracker (BD/T) mount. The BD/T then follows this track and acquires the debris with its one degree field of view camera. The operator then brings the debris onto the boresight camera and takes position readings to update the track file. After several readings along the track, a very accurate element set can be generated for this piece of debris.

"Determination of Debris Albedo from Visible and Infrared Brightness"
J.V. Lambert
Space Debris Detection and Mitigation, Proceedings, SPIE 1951, April 1993

The Air Force Phillips Laboratory is conducting measurements to characterize the orbital debris environment using wide-field optical systems located at the Air Force's Maui, Hawaii, Space Surveillance Site. Conversion of the observed visible brightness of detected debris objects to physical sizes requires a knowledge of the albedo (reflectivity). A thermal model for small debris objects has been developed and is used to calculate albedos from simultaneous visible and thermal infrared observations of cataloged debris objects. The model and initial results will be discussed.

"Orbiting Space Debris: Dangers, Measurement and Mitigation"
R. McNutt
Phillips Laboratory Technical Report, PL-TR-92-2146, June 1992

Space debris is a growing problem. Accumulation of objects in Earth orbit threatens space systems through the possibility of collision and runaway debris multiplication. The amount of debris in orbit is uncertain due to the lack of information on the population of debris between 1 and 10 centimeters diameter. Collisions with debris even smaller than 1 cm can be catastrophic due to the high orbital velocities involved. Research efforts are underway at NASA, United States Space Command and the Air Force Phillips Laboratory to detect and catalog the debris population in near-Earth space. Space debris is a serious problem with large economic, military, technical and diplomatic components. Actions need to be taken now to: determine the full extent of the orbital debris problem; accurately predict the future evolution of the debris population; decide the extent of the debris mitigation procedures required; and implement these policies on a global basis via an international treaty. Action must be initiated now, before the loss of critical space systems such as the Space Shuttle or the Space Station.

"Recent Results of a Reacquisitioning Debris Search"
E.C. Pearce, M.S. Blythe, D.M. Gibson, and P.J. Trujillo
AIAA 31st Aerospace Sciences Meeting and Exhibit, AIAA-93-0161, 11 January 1993

In May 1991, MIT Lincoln Laboratory's Experimental Test System undertook a unique series of optical debris measurements. The first phase of the observing program was designed to demonstrate the ability to detect, track, and generate accurate element sets for debris-sized objects. Early searching targeted specific sun-synchronous debris clouds, including the NIMBUS-6 rocket body breakup. In order to achieve maximum sensitivity, these searches used a technique called "pseudo-tracking." When searching in this mode, the telescope tracks along orbits similar to previously cataloged debris cloud members.
Later, a new series of unbiased "stare and chase" searching was performed. This observing mode combined the best features of both the traditional high-volume searches and the pseudo-tracking searches. In both programs, when an object was detected, the operator would manually acquire and track the object. Once acquired, the object would be tracked to the horizon, generating sufficient metric data for an accurate orbit determination. A comparison

between the observed and cataloged debris distribution has been made. Additionally, a careful analysis has been performed to assess the quality of the orbits determined from these short initial tracks.

"Results of Stare and Chase Debris Search at the Experimental Test System"
E.C. Pearce, M.S. Blythe, D.M. Gibson, and P.J. Trujillo
1993 MIT Lincoln Laboratory Space Surveillance Workshop Proceedings, Project Report STK-206, Vol. II, March 1993

Since May 1991, MIT Lincoln Laboratory's Experimental Test System has been performing a unique series of optical debris measurements. The first phase of the observing program developed the ability to detect, track, and generate accurate element sets for debris sized objects. Using these techniques, a series of unbiased "stare and chase" searches were started in 1992 and continue to date. For the first time, this program has allowed detailed analysis of the uncataloged debris population. Initial results indicate that uncataloged debris are tightly distributed near traditional operational inclinations. However, the orbital distribution in eccentricity differs significantly from that of the Space Surveillance Catalog. Specifically, a much higher fraction of debris occupies moderate and high eccentricity orbits. The ETS has a unique ability to detect, acquire, track, and maintain a catalog of faint debris. Further, its capability to do multicolor, high-speed photometry allows detailed study of the physical properties of uncataloged objects. Accurate estimates of the size, rotation rate, drag coefficient, albedo, and composition for individual debris objects have been made. Thus, properties of the cataloged and uncataloged orbital population can be compared.

"Space Debris Measurements: Phase One Final Report"
E.C. Pearce, M.S. Blythe, D.M. Gibson, and P.J. Trujillo
1994 MIT Lincoln Laboratory Space Surveillance Workshop Proceedings, Project Report STK-221, Vol. I, April 1994

This report documents the results of Phase One of the Phillips Laboratory Debris Measurement Program at the Experimental Test System. Observationally, the primary goals of the program were to develop and implement techniques to detect and track small, previously uncataloged space debris. Additionally, techniques were developed to monitor sensor performance and understand observational biases. During the program, a total of 840 objects were detected, with 346 objects being previously uncataloged. An analysis of the orbital distribution of the tracked objects has shown that the orbital distribution of the observed space population is significantly more eccentric than the orbital distribution of the Space Surveillance Catalog. Long term tracking of several pieces has shown that the orbital dynamics of many smaller debris objects are poorly modeled by currently used propagation models. Finally, a lower limit on the space population larger than 10 cm has determined that the catalog is incomplete by at least a factor of 1.6.

"Investigations into Methods to Measure Orbital Debris"
J. Secary
Phillips Laboratory Technical Report, PL-TR-91-1030, September 1991
(Distribution limited to U.S. Government agencies only)

This report documents results of a project aimed at investigating space debris measuring methods and identifying the most viable method to measure debris. Various space and earth-based debris measuring devices have been researched and evaluated. These devices are active radar systems, passive and active optical systems, and spacecraft-mounted impact sensors. To evaluate the debris measuring devices, a set of criteria was established. These criteria consisted of operational cost, availability, and capability of each system to provide the needed large volumetric coverage of space to acquire debris data. Based on this comparative analysis, it was concluded that a combination of earth-based radars and space-based "piggy-back" optical sensors is most suitable for measuring the debris environment. During this study, it became apparent that a problem exists in the current space debris data-base (ENVIRONET). Both DoD and NASA are actively collecting debris data for their own specific operational use. However, the most current debris data are often omitted from the database. To address this problem, the author recommends incorporating all current data into a national debris database and formalizing procedures for updating the database.

"Application of the Hough Transform to Track Detection"
M. Svedlow and P. Semenza
31st Aerospace Sciences Meeting and Exhibit, AIAA-93-0163, 11 January 1993

A technique based on the Hough transform has been developed to detect space debris tracks in telescope images. The process has been simulated and initially verified using actual sequences of telescope image data from two different sources. Results show that the technique can detect tracks occurring across multiple image frames. Important features of the process are that it can detect discontinuous track segments and that it performs successfully for a variety of image recording formats and noise levels.

"Determining Satellite Close Approaches"
S. Alfano
Journal of the Astronautical Sciences, Vol. 41, No. 2, April-June 1993

This paper presents a numerical method to evaluate close approaches of two satellites. The algorithm is based on a space curve modeling technique originally developed by Overhauser, presented here as an independent derivation. The method to determine minimum spacing between two space objects is based on creating a relative distance waveform, $\delta(t)$, versus time. The waveform is produced from either uniform or arbitrarily spaced data points, from which intervals of close approach are obtained by extracting the real roots of a localized cubic polynomial. This method is free of both transcendental equations and the computation of acceleration terms of the two objects of interest. For this study a close approach truth table is constructed using a 0.1 second sequential step along the orbits, then differencing the two position vectors. The close approach entrance and exit times for an ellipsoidal quadratic surface are then located using a piecewise linear interpolator, and serve as a benchmark for comparison. The simulation results show this algorithm produces encounter times almost identical to those in the truth table, with a 99.84% reduction in computer runtime. The results, created from real orbital data, include solution sets for three operational uses of close-approach logic. For this study, satellite orbital motion is modeled using first-order specular perturbations caused by mass anomalies.

"Determining Satellite Close Approaches: Part II"
S. Alfano
AAS/AIAA Spaceflight Mechanics Meeting, Proceedings, AAS 94-108, 14 February 1994

Improvements to the original Alfano/Negron Close Approach Software (ANCAS) tool are presented that increase accuracy and/or step size. Minimum spacing between two satellites is determined by creating a time-dependent third-order relative-velocity waveform produced from adjoining pairs of distances, velocities, and accelerations. Times of closest approach are obtained by extracting the real roots of the localized polynomial with the associated distances reconstructed from a set of fifth-order polynomials. Close approach entrance and exit times for an ellipsoidal quadratic surface are found using a similar process. Both methods require a simplified computation of acceleration terms of the objects of interest. For this study a close approach *truth* table is constructed using a 0.1s sequential step along the orbits and differencing the two position vectors. The simulation results show this algorithm produces encounter times almost identical to those of the *truth* model, with a 98%

reduction in computer runtime. The results are created from real orbital data and include solution sets for three operational uses of close-approach logic. Satellite orbital motion is modeled by, but not limited to, first-order secular perturbations caused by mass anomalies.

"Analytical Prediction of Space Debris"
D.J. Amdahl
Space Debris Detection and Mitigation, Proceedings, SPIE 1951, April 1993

The J.N. Johnson void growth fracture model has been implemented into *Magi* to develop a capability to predict orbital debris generated from hypervelocity impacts or programmed explosions. *Magi* is a hydrodynamic code based on Smoothed Particle Hydrodynamics (SPH). This paper demonstrates advances in modeling fragmentation by calculating the debris environment generated from aluminum spheres impacting thin aluminum sheets representing debris shields. The shape of the debris cloud, fragment size, and fragment velocities are compared to the experimental work documented by Piekutowski. Plots of fragment mass versus cumulative number of fragments are also presented. Calculations of flyer plate experiments are presented and discussed to provide a foundation for understanding the fracture model and its input parameters. The results show that SPH is quite natural for modeling the fragmentation for these experiments.

"Fractals and Debris Distributions"
L. Baker and F.A. Allahdadi
Orbital Debris Monitor, Vol. 5, No. 2, April 1992

Fracture has been shown to have fractal character. This is used to guide the development of fragmentation models to be used in characterizing spallation. First, the basic ideas of fractals (and multifractal measures) are discussed. Applications to the prediction of spall mass distributions are shown and discussed.

"Fracture and Spall Ejecta Mass Distribution: Lognormal and Multi-Fractal Distributions"

L. Baker, A. Giancola, and F.A. Allahdadi

Journal of Applied Physics, Vol. 72, No. 7, 1 October 92

Numerous distributions (Mott, exponential, bimodal) have been proposed on the basis of geometrical or semi-empirical grounds as suitable for characterizing the mass distribution from fracture or spallation. It is argued here that the lognormal distribution is particularly suitable on the basis of a number of considerations: empirical fits, the fractal character of fracture, and the geometrical arguments when carried to their logical conclusion. We explain the deviations from the lognormal distribution as due to the finite thickness of the shell, which violates the scale-independence requirement for exact fractal behavior and introduces multifractal character to the spallation process. A plausibility argument for the observed relationship between ductility and the shape of the distribution is offered.

"Physical Fragmentation Modeling"

L. Baker

Phillips Laboratory Technical Report, PL-TR-92-1057, April 1993

(Distribution limited to U.S. Government agencies only)

The characterization of fragments from spallation due to high-velocity impacts and explosions is of great practical importance for the mitigation of the debris environment in space and the design of both warheads and armor protection against warheads for aircraft and other vehicles. Work in this field has generally been highly empirical, with fits to experiments serving as almost the sole attempts at analysis. In this effort, physical considerations, including the established fractal character of fracture, were used to develop models for fragmentation. By developing theoretically based models, the understanding of fragmentation processes should improve, permitting higher confidence estimates of system behavior. This effort focuses on multifractal models of fragmentation as providing the most realistic simulations. Experiments to clarify the physics of fragmentation are proposed. Differences between fragment distributions due to explosions and impact are discussed. The role of melt and vaporization in hypervelocity impact is considered. The question of how to choose, a priori, model parameters to duplicate physical systems is the greatest remaining challenge.

"Debris Analysis Workstation: A Modeling Environment for Studies on Space Debris"
K. Bellman and A.E. Reinhardt
First European Conference on Space Debris, Proceedings, ESA SD-01, Darmstadt, Germany, April 1993

The purpose of the Debris Analysis Workstation (DAW) is to support studies of the hazards of space debris for operational orbital space systems, specifically on-orbit event analysis, intercept test predictions, and long-term debris flux predictions. DAW supports two levels of users: first, the scientists and analysts who develop and evaluate space debris environment models; second, users who are responsible for the operation of space systems or other space test programs. Like many other complex simulation and analysis tasks, there is no single analysis or model that can address space debris problems. Hence, a collection or library of tools and models is required. However, unlike many other special application modeling environments, DAW seeks to do more than provide a basic library of tools and models, accessible through a common user interface. DAW provides the user with a set of "intelligent user interface functions" [Bellman, 91; Landauer, 92] that help the user to select, adapt, and integrate the diverse software and modeling resources required for debris studies. In addition, the environment is developed so that different models can be concurrently run and explicitly compared.

"An Introductory Analysis of Satellite Collision Properties"
K. Carlton-Wippern
AAS/AIAA Astrodynamics Specialist Conference, AAS 93-748, 16 August 1993

This paper addresses a probabilistic approach in assessing the possibilities of a satellite collision occurring due to relative trajectory analyses and probability density functions representing the satellites' position/momentum vectors. The paper is divided into two parts: Static and Dynamic Collision Probabilities. In the Static Collision Probability section, the basic phenomenon under study is: given the mean positions and associated position probability density functions for two objects, calculate the probability that the two objects collide (defined as being within some distance or volume of each other). The paper presents the classic Laplace problem of the probability of arrival, using standard uniform distribution functions. This problem is then extrapolated to show how "arrival" can be classified as "collision," how the arrival space geometries map to collision space geometries, and how arbitrary position density functions can then be included and integrated into the analysis. In the dynamic Collision Probability section, the nature of collisions based upon both trajectory and energy considerations is discussed, and that energy states alone cannot be used to completely describe whether or not a collision occurs. This fact invalidates some earlier work on the subject and demonstrates why Liouville's theorem cannot be used, in general, to describe the constant density of the position/momentum space if such a collision may occur. Future position probability density functions are then shown to be the convolution of the current position and momentum density functions (linear analysis), and the paper further demonstrates the dependency of the future position density functions on time. Strategies for assessing the collision probabilities for two point masses with uncertainties in position and momentum at some given time, and these integrated with some arbitrary impact volume schema, are then discussed. This presentation concludes with the formulation of a high level design for a Collision Requirements and Satellite Trajectory Analysis (or CRYSTAL) computational computer program, prototype software package.

"Debris Evolution and Lifetime Following an Orbital Breakup"
V. Chobotov and D. Spencer
Journal of Spacecraft and Rockets, Vol. 28, No. 6, November - December 1991

This paper is an overview of the space debris modeling techniques and tools used at The Aerospace Corporation in support of the Air Force space debris efforts. A discussion is presented of the software tools *IMPACT*, which does the breakup analysis, and *DEBRIS*, which does collision hazard assessment. Additionally, some effects of atmospheric drag on debris environment are presented.

"Disposal of Spacecraft at the End of Life in Geosynchronous Orbit"
V. Chobotov
Journal of Spacecraft and Rockets, Vol. 27, No. 4, July - August 1990

A number of national and international organizations have adopted a policy of removing spacecraft at the end of life from the geosynchronous ring. However, a resolution of several technical issues still remains before an international policy can be developed and implemented by all users of geosynchronous orbits. The present study reviews the cataloged population of objects in the geosynchronous ring. The probability of collision is computed as a function of range and orbital inclination of an object. Long-term stability of supersynchronous disposal orbits and of the geopotential stable points is examined. Several disposal options are considered. The results of the study show that the use of the supersynchronous orbits for disposal purposes is economical and effective in significantly reducing the collision hazard. The use of the geopotential stable points for disposal of spacecraft at the end of life, on the other hand, was found to be impractical.

"Dynamics of Orbiting Debris Clouds and the Resulting Collision Hazard to Spacecraft"
V. Chobotov
Journal of the British Interplanetary Society, Vol. 43, 1990

The dynamics of a cloud of particles resulting from a breakup of an object is presented. Linearized equations of motion are used to obtain the shape and volume of the cloud as a function of time and the initial debris particle spread velocities. Spatial density is calculated for representative breakup models. The probability of collision with a spacecraft in orbit is examined. The effects of Earth's oblateness on the temporal evolution of the cloud are included.

"The Effects of Satellite Bunching on the Probability of Collision in Geosynchronous Orbit"
V. Chobotov and C.G. Johnson
First European Conference on Space Debris, Proceedings, ESA SD-01, Darmstadt, Germany, April 1993

The rapid increase in the satellite population in geostationary earth orbit (GEO) is a matter of international concern, in part because of increased collision hazard. Collocated satellite pairs in GEO experience natural drift requiring periodic station keeping impulses, leading to similar trajectories and close encounters. To assess this risk, a procedure was devised which ranks satellite pairs in GEO according to the highest number of encounters over an extended time interval. Probability of collision was determined by a geometric and a stochastic approach. It was found that many pairs of satellites in GEO remain in close proximity and experience many close approaches over time. The top 10 pairs in terms of closest encounters were identified and mean time to collision based on encounter statistics was determined. Results of the study suggest that the bunching of active or inactive satellites at certain longitudes is a significant effect to be considered in the assessment of the collision hazard in the geosynchronous ring.

"Quantifying the Orbital Debris Environment"
P. Dao, R. McNutt, F.M. Jonas, P. Soliz, and K.W. Yates
Acta Astronautica, Vol. 26, No. 7, April 1992

The orbital debris environment is of increasing concern to users of space. Models describing this environment depend on accurate and precise measurements of debris for all sizes and altitudes. This paper presents the assessment of an environment model, developed by NASA, and the uncertainties of that model. The uncertainties are shown to be dominated by the lack of knowledge of the debris environment. A Phillips Laboratory (Geophysics Directorate) measurement program is described that will enhance man's understanding of the debris environment. It uses the 2.54 m telescope located at Wright Laboratory (Wright-Patterson AFB, Ohio).

"Characterization and Correlation of Hypervelocity Impact Debris: Naval Research Laboratory Tests"

B.H. Fortson and S.R. Maethner

Phillips Laboratory Technical Report, PL-TR-92-1063, December 1993

(Distribution limited to U.S. Government agencies and their contractors only)

Debris Characterization is the process of describing an impact debris population with a few parameters. In this report, debris from impact experiments performed on satellite mock-ups at the Naval Research Laboratory (NRL) is characterized. A parametric model is constructed, quantifying the influence of test variables such as projectile velocity and strike angle on the debris produced by impact. The effectiveness of exponential and log-normal distributions in describing the debris population is assessed. The *IMPACT 1.0* debris prediction program is applied to the NRL debris, and the predictions compared with actual results.

"Characterization of Hypervelocity Impact Debris: Impact Tests from the FRGIT Series"

B.H. Fortson and S.R. Maethner

Submitted to Journal of Testing and Evaluation

Debris Characterization, in the context of this report, is the description of a body of impact debris using a few parameters. Such characterization of debris from hypervelocity impact events is an important prerequisite for the construction of analytical or empirical predictive models of those events. These models cannot be evaluated without a body of test data with which to compare their predictions. This report augments that data base by using curve fitting techniques to characterize debris resulting from impact tests from the FRGIT test series. Also, a comparison of the effectiveness of lognormal and exponential fits to the mass distribution data is made.

"Characterization of Hypervelocity Impact Debris: Naval Research Laboratory Tests"
B.H. Fortson and J.E. Winter
Journal of Testing and Evaluation, Vol. 21, No. 5, September 1993

Characterization of debris from hypervelocity impact events is an important prerequisite for analytical or empirical predictive modeling of those events. One feature of a useful model would be its ability to predict the characteristics of the debris cloud produced by the impact, and this feature cannot be evaluated without a body of test data with which to compare the analytical predictions. In the current effort, debris produced by hypervelocity impact experiments at the Naval Research Laboratory (NRL) is collected and described. An attempt is also made to construct a parametric model of the data in order to assess the effectiveness of this approach. A model based on a linear relationship is seen to perform well, while a parabolic relationship performs less well, and a bilinear relationship performs poorly. A lognormal distribution is seen to describe the debris more effectively than an exponential distribution. However, the performance of the exponential distribution is seen to improve when the very largest fragments are removed from consideration.

"Space Debris Characterization in Support of a Satellite Breakup Model"
B.H. Fortson, J.E. Winter, and F.A. Allahdadi
Fifth Annual Workshop on Space Operations Applications and Research (SOAR '91), NASA Conference Publication 3127, Vol. II, July 1991
and
Phillips Laboratory Technical Report, PL-TR-92-1044, September 1992

The Space Kinetic Impact and Debris Branch has begun an ambitious program to construct a fully analytical model of the breakup of a satellite under hypervelocity impact. In order to provide empirical data with which to substantiate the model, debris from hypervelocity experiments conducted in a controlled laboratory environment has been characterized to provide information on its mass, velocity, and ballistic coefficient distributions. Data on the debris have been collected in one master data file and a simple FORTRAN program allows users to describe the debris from any subset of these experiments that may be of interest to them. A statistical analysis has been performed, allowing users to determine the precision of the velocity measurements for the data, as well as those data obtained from the explosion or collision of spacecraft in low earth orbit.

"Trade-Offs in Mass and Effectiveness in Satellite Shielding: A Design Approach"
B.H. Fortson
Phillips Laboratory Technical Report, PL-TR-92-1020, August 1992

The optimal design for a debris shield for a spacecraft is discussed. A shield 3-ft thick would provide excellent protection but would be prohibitively expensive to deploy. Conversely, using no shield at all would be highly economical but would provide poor protection from impacts. Somewhere between these two extremes is a shielding design that combines effectiveness with practicality. A rationale for determining this optimal configuration is outlined. Consider the case for which the thickness of a shield determines its mass and its debris-stopping effectiveness. A shield is considered to have failed when its ballistic limit is exceeded, that is, when it is penetrated. Using this criterion, along with existing models of the orbital debris environment, computer simulations can determine the probability that a given shield will be penetrated by debris over a 1-yr time span. This probability can be expressed as a function of the shield thickness. The shield thickness corresponding to the maximum acceptable probability of failure is the optimum thickness. This report outlines an experimental plan for applying this rationale.

"Analysis of the Non-Stationary Debris Cloud Pinch Zone"
A.B. Jenkin
AAS/AIAA Astrodynamics Specialist Conference, AAS 93-625, 16 August 1993

This paper presents an analysis of the underlying causes and features of the debris cloud non-stationary pinch zone. This pinch zone is classified as "non-stationary" because it drifts inertially as the debris cloud flies through it. The more familiar half- and whole-revolution pinch zones are classified as "stationary" because they do not move inertially under Keplerian motion. It was found that the non-stationary pinch zone consists of a curved surface, or sheet, of positions inside the debris cloud in which debris density becomes very large, and in the case of Keplerian motion approaches infinity. The analysis was based on the use of Jacobians to determine regions of infinite density and to expose the complex relative motion that underlies the phenomenon. The understanding of pinch zones is important because, due to their characteristic high fragment density, they pose the greatest hazard to orbiting assets.

"DEBRIS: A Computer Program for Debris Cloud Modeling"
A.B. Jenkin
44th Congress of the International Astronautical Federation, IAA.6.3-93-746, 16 October 1993

The computer software *DEBRIS* is a tool for modeling orbital debris clouds which have been formed by fragmentation events. It permits the assessment of the collision hazard posed to orbiting spacecraft by fragments in a given cloud. The most recent versions, 3.0 and 3.1, feature a significant improvement in accuracy compared to earlier versions. Versions 1.0 to 2.0 used approximate methods to model the dispersion of a debris cloud around the earth and to compute probability of collision. These approximations included assumptions on the geometrical shape of a debris cloud and representation of cloud dynamics by linearized orbital motion. Versions 3.0 and 3.1 use a technique which is a generalization of the methods of Heard and Housen. This method is based on statistical continuum dynamics and does not suffer from the inaccuracies that are latent to the assumptions used in previous versions of *DEBRIS*. Unlike other similar, recently developed software, the method is not limited to Keplerian motion. Orbital perturbations can be included to the extent that the resulting computational burden can be tolerated. This is an important feature so that the location of debris cloud pinch zones, i.e., regions of high debris density, can be accurately determined and avoided by spacecraft. The latest version of *DEBRIS*, 3.1, generates data that is useful to both mission planning and spacecraft shielding design. This data includes histories of debris density, encountered debris fluence, and distributions of fragment mass and collision directionality. This paper presents a description of the theory and techniques incorporated in the most recent version of *DEBRIS*.

"Theoretical and Practical Issues in Software for Space Debris Modeling"
C. Landauer
First European Conference on Space Debris, Proceedings, ESA SD-01, Darmstadt, Germany, April 1993

This paper describes critical issues in the modeling of space debris. The United States is tracking thousands of objects currently and assessing the threat to planned space activities by computing hazard probabilities. Fundamental parts of these calculations are the programs that model different kinds of space interaction events and the resulting hazard, both to current and planned space activities and to people and structures on the ground. We describe results of a detailed mathematical analysis of a prominent model for space debris, discuss modeling issues that confront any space debris model, and some separate issues that confront implementations of such models.

"High Strain Lagrangian Hydrodynamics. A Three-Dimensional SPH Code for Dynamic Material Response"

L.D. Libersky, A.G. Petschek, T. Carney, J. Hipp, and F.A. Allahdadi

Journal of Computational Physics, Vol. 109, No. 1, November 1993

and

Phillips Laboratory Technical note, PL-TN-92-1054, March 1993

MAGI, a three-dimensional shock and material response code which is based on smoothed particle hydrodynamics (SPH) is described. Calculations are presented and compared with experimental results. The SPH method is unique in that it employs no spatial mesh. The absence of a grid leads to some nice features such as the ability to handle large voids. Both of these features are important in the tracking of debris clouds produced by hypervelocity impact - a difficult problem for which SPH seems ideally suited. We believe this is the first application of SPH to the dynamics of elastic-plastic solids

"Simulating HVI Effects on Structures Using the Smoothed Particle Hydrodynamics Code"

L.D. Libersky, T. Carney, and F.A. Allahdadi

Fifth Annual Workshop on Space Operations Applications and Research (SOAR '91), NASA Conference Publication 3127, Vol. II, July 1991

Analysis of interaction occurring between space debris and orbiting structures is of great interest to the planning and survivability of space assets. Computer simulation of the impact events using hydrodynamic codes can provide some understanding of the processes but the problems involved with this fundamental approach are formidable. First, any realistic simulation is necessarily three-dimensional, e.g., the impact and breakup of a satellite. Second, the thickness of important components such as satellite skins or bumper shields are small with respect to the dimension of the structure as a whole, presenting severe zoning problems for codes. Thirdly, the debris cloud produced by the primary impact will yield many secondary impacts which will contribute to the damage and possible breakup of the structure. Characterization of the debris cloud requires accurate fragmentation modeling as well as accurate tracking of the fragments through large regions of void. For these reasons hydrodynamic simulation of hypervelocity impact and breakup of orbiting structures is extremely difficult. We have approached the problem by choosing a relatively new computational technique that has virtues peculiar to space impacts. The method is called Smoothed Particle Hydrodynamics (SPH). In this paper we describe the SPH method and why we believe that it can be used to answer many questions concerning the survivability of space assets due to kinetic impacts. We also present several calculations to show the power of SPH towards such problems.

"Fundamentals of Smoothed Particle Hydrodynamics (SPH)"
C.P. Luehr and F.A. Allahdadi
32nd Aerospace Sciences Meeting, AIAA-94-0066, 10 January 1994

Smoothed Particle Hydrodynamics (SPH) models the motion of a continuous medium as a finite system of moving particles. The method has some significant advantages because it does not need a computational grid. In this particle model, each particle has the usual variables such as mass density, specific internal energy, pressure, stress tensor, and velocity gradient in order to approximate the state of the medium at its position. Two new methods for deriving the governing equations for particle models are presented. The Potential Energy Method for compressible nonviscous fluids in adiabatic flow uses a smoothing procedure on particle masses to find mass densities, and uses the fact that specific internal energies are functions of mass density only. The governing equations are derived from a potential energy function obtained by summing all particle internal energies. The Energy Balance Method uses smoothing methods to find mass densities and momentum densities, from which velocity gradients are found. With no further interpolation procedures, all the governing equations except one are found directly from the continuum equations. The momentum equations are derived from the specific internal energy equations by applying the law of total energy conservation.

"Numerical Well-Conditioned Expressions for Isotropic Tensor Functions"
C.P. Luehr and F.A. Allahdadi
Computer Methods in Applied Mechanics and Engineering, Vol. 104, May 1993

A numerically well-conditioned expression for an isotropic tensor function of a symmetric second order tensor is derived in the cases of two and three dimensions, and is also stated for *n* dimensions. The derivation starts with the expression of the tensor function in its spectral representation in terms of projection operators onto eigenspaces of the tensor. The spectral representation however, is ill-conditioned when any eigenvalue is too close to any differing eigenvalue. A rearrangement and recombination of terms gives the desired result, which is a well-conditioned expression.

"FY92 Technical Verification and Validation of the DEBRA Code"
L. McKee, W. Margopoulos, and S. Graeff
Phillips Laboratory Technical Report, PL-TR-92-1072, October 1993
(Distribution limited to U.S. Government agencies and their contractors only)

The Technical Verification and Validation (TV&V) methodology recommended in the FY91 program was implemented and applied to two releases of *DEBRA*, Version 1.0 and Version 1.1. The physics models contained in *DEBRA*, Version 1.0 were analyzed in detail, while TV&V testing was performed on *DEBRA*, Version 1.1. Analysis of the physics models revealed some modeling errors and some areas where the models could be improved. Several physics modeling issues were not resolved in this report and remain as significant open issues. The testing utilized a top-down approach and was coordinated with bottom-up testing performed by The Aerospace Corporation for a greater confidence in the operational performance of the *DEBRA*, Version 1.1 code. The testing revealed some anomalies and assisted in prioritizing future improvements.

"Correlation of an Empirical Spacecraft Breakup Model's Predictions with Data from Hypervelocity Impact Experiments"
S.R. Maethner
Space Debris Detection and Mitigation, Proceedings, SPIE 1951, April 1993

An accurate prediction of the short and long term man-made orbital debris environment depends on the fidelity of spacecraft breakup models. These models provide post-breakup information for spacecraft collisions and explosions, including the number of fragments produced and the state vectors for each fragment. One way to verify the predictive capabilities of these models is to compare their predictions with the results of well characterized hypervelocity impact experiments. This paper compares the predictions of the empirically based spacecraft breakup model *IMPACT 2.02* to the outcome of several hypervelocity impact experiments. The experimental data and the model predictions are analyzed and correlated, and the discrepancies are identified.

"Analysis of Energy Dissipation and Deposition in Elastic Bodies Impacting at Hypervelocities"

D.F. Medina and F.A. Allahdadi

Fifth Annual Workshop on Space Operations Applications and Research (SOAR '91), NASA Conference Publication 3127, Vol. II, July 1991

A series of impact problems were analyzed using the Eulerian hydrocode CTH. The objective was to quantify the amount of energy dissipated locally by a projectile-infinite plate impact. A series of six impact problems were formulated such that the mass and speed of each projectile were varied in order to allow for increasing speed with constant kinetic energy. The properties and dimensions of the plate were the same for each projectile impact. The resulting response of the plate was analyzed for global KE, global momentum, and local maximum shear stress. The percentage of energy dissipated by the various hypervelocity impact (HVI) phenomena appears as a relative change of shear stress at a point away from the impact in the plate.

"Numerical Simulations of Hypervelocity Impact Experiments at Velocities in Excess of 10 km/s Involving Single and Double Plates"

D.F. Medina and S.R. Maethner

Space Debris Detection and Mitigation, Proceedings, SPIE 1951, April 1993

Well-controlled hypervelocity impact experiments, conducted in support of the Space Station Shielding Program, were numerically modeled using two sophisticated hydrocodes, the multi-dimensional hydrodynamics code CTH and the Smoothed Particle Hydrodynamics code (SPH). The experiments simulated the impact of space debris on single and double (Whipple Shield) plate configurations. Impact velocities on the order of 10 km/s were applied to gram sized flier plates and spherical projectiles that struck thin (less than 1 cm) aluminum and steel plates. Computational predictions of the debris cloud dynamics and plate damage for these experiments were analyzed and correlated with the data obtained from pulsed laser photographs.

"Numerical Simulations of Hypervelocity Impact Experiments Involving Single Plates and Single Whipple Bumper Shields"

D.F. Medina and S.R. Maethner

Phillips Laboratory Technical Report, PL-TR-93-1027, October 1993

Well-controlled hypervelocity impact experiments, conducted in support of the Space Station Shielding program, were numerically modeled using two sophisticated hydrocodes, the multidimensional hydrodynamics code (CTH) and the Smoothed Particle Hydrodynamics code (SPH). The experiments simulated the impact of space debris on single shields and single Whipple bumper shield plate configurations. Impact velocities on the order of 10 km/s were applied to gram-sized flier plated and spherical projectiles that struck thin (<1 cm) aluminum, titanium, and steel plates. Computational predictions of the debris cloud dynamics and plate damage for these experiments were analyzed and correlated with the data obtained from pulsed laser photographs and high-speed X-ray photography. Computational results of both hydrocodes were compared to each other.

"Cylindrical Smoothed Particle Hydrodynamics"
A.G. Petschek and L.D. Libersky
Journal of Computational Physics, Vol. 109, No. 1, November 1993

Smoothed Particle Hydrodynamics (SPH) is formulated in two-dimensional axisymmetric coordinates. Starting with a three-dimensional Cartesian representation of SPH we integrate out the angular component and find a two-dimensional cylindrical description. A smoothed "particle" in this formulation becomes a smoothed "torus." The hoop stress, resulting from interactions within the toroidal ring, is a natural consequence of the derivation. No pathological behavior is observed at the symmetry axis. The formulation has been extended to include the entire stress tensor, not just the pressure, and is therefore applicable to a wide range of materials and flow speeds. Three calculations are presented and compared to known results.

"Long Term Orbital Debris Environment Sensitivity to Spacecraft Breakup Parameters"
A.E. Reinhardt, W. Borer, and K.W. Yates
29th Plenary Meeting of the Committee on Space Research (COSPAR), World Space Congress, Washington D.C., 28 August - 5 September 1992

The long term prediction of the orbital debris environment depends fundamentally on the dynamics of spacecraft breakups. These processes provide the numbers, initial velocities, positions, and ballistic coefficients for newly formed debris fragments. Efforts are ongoing to model satellite breakup phenomena using a variety of models with varying degrees of complexity. This paper provides a comparison of four of the empirical or faster running models, then suggests an Analysis of Variance (ANOVA) test matrix approach to perform an initial sensitivity analysis of these models. The results of two of the models against the test matrix are discussed, as well as how differences in initial breakup conditions affect the sensitivity of the long term orbital debris environmental prediction.

"Potential Effects of the Space Debris Environment on Military Space Systems"
A.E. Reinhardt
Preservation of Near-Earth Space for Future Generations
American Academy of Arts and Sciences, University of Chicago, 24 June 1992

The U.S. Department of Defense is in the first phase of a research effort to characterize the space debris environment and establish the potential threat level debris represents to current and future DoD space systems. The U.S. Air Force Phillips Laboratory is acting as the technical lead for this research program. The Phase 1 effort, characterization of the debris environment, is scheduled to complete at the end of Fiscal Year 1993. Phase 1 emphasizes both the measurement and modeling efforts needed to characterize the current debris environment down to 0.1 cm and to project the future environment and its impact on the survivability of current and planned systems. In parallel, policy efforts have led DoD space designers to implement cost effective debris minimization measures for future systems. A joint effort with NASA to develop a Space Debris Minimization and Mitigation Handbook is also geared to fielding "debris clean" space systems. The threat, however, must be well defined and significant before more costly measures are implemented. This paper will discuss the background of the DoD space debris research program, the status and goals of the Air Force Phillips Laboratory measurement and modeling efforts, and the objectives and status of the Space Debris Minimization and Mitigation Handbook.

"Projected Threat of the Space Debris Environment to Selected DoD Space Systems"
A.E. Reinhardt and K.W. Yates
Space Debris Detection and Mitigation, Proceedings, SPIE 1951, April 1993

Modeling of the space debris environment is critical to providing spacecraft designers with projections of the environment over the planned lifetime of a system. Understanding how the debris environment is projected to change over time allows spacecraft designers and managers the ability to implement responsive design mitigation measures into their systems. This paper develops a strategy for assessing the projected threat of the space debris environment for particular space systems. First, an historical simulation of the debris environment is made using available empirical models. For the system under study, the planned operational loss rates are also identified based on mission operational requirements and projected launch mission models. Generally, the system designers will plan to replace components at a matching rate to maintain required system performance. A threshold debris growth factor is then identified giving the percentage increase over the current historical environment that will produce a debris collision rate equal to the planned spacecraft loss rate as identified from the mission operational requirements. Using this approach, the overall threat of the projected debris environment for particular space systems is couched in terms spacecraft managers can appreciate, that of replacements required over a given period of time.

"Space Debris Hazard Software: Program Impact Version 1.0B"

M.E. Sorge

The Aerospace Corporation, Aerospace Report No. TOR-0091(6909-04)-1, Los Angeles, California, January 1991

(Distribution limited to U.S. Government agencies and their contractors only)

Program *IMPACT* is used to model on-orbit explosions and hypervelocity collisions. Given the pre-breakup state vectors of the object or objects involved, *IMPACT* determines the amount and motion of the resulting debris. *IMPACT* uses several different fragment and spread velocity distributions to model collisions and explosions. The fragment distributions from collisions and explosions will be described, as well as the fragment spread velocity distributions for the various types of collisions and explosions. Descriptions are given for the breakup scenarios used and how the fragmentation and spread velocity models are combined to create them. *IMPACT* and its associated post-processors are integrated through several shell programs. These shells coordinate the interfaces between each of the processors and between the processors and the user. A user can therefore operate the system without in-depth knowledge of these files.

"Space Debris Hazard Software: Program Impact Version 2.0 Breakup Model"

M.E. Sorge

The Aerospace Corporation, Aerospace Report No. TOR-92(2076)-2, Los Angeles, California, April 1992

(Distribution limited to U.S. Government agencies and their contractors only)

Program *IMPACT* contains a model for simulating orbital altitude explosions and hypervelocity collisions. The model first was developed after the Delta-180 test in 1986. Modelling of that test and the P-78 antisatellite (ASAT) test in 1985 had been done by hand calculations. Incorporation into a single computer program of the various models used to simulate the different aspects of orbital fragmentations significantly decreased analysis times and allowed greater complexity in the model. The basic approach in the *IMPACT 2.0* model is to represent fragmentations in a general manner. In this way, an overall idea of the results of a large variety of fragmentation events may be modeled efficiently. To achieve this requires a combination of empirical expressions, analytic solutions, and applications of conservation laws. These are integrated in the *IMPACT 2.0* model to simulate the interdependence of various parts of the fragmentation process on one another. Due to the generalized, empirical treatment of the fragmentation process, little specific data on the structural makeup of the fragmenting object are used. Masses, and the basic type of the larger object, are all the structural information required. This generalized treatment of the fragmentation process requires special considerations when the fragmentation model's results are interpreted. Emphasis must be placed on the overall characteristics of the results representing a "typical" result from the fragmentation in question. This paper documents the fragmentation model used in *IMPACT 2.0*. All elements of the modeling approach (including governing equations and assumptions) are presented.

"Space Debris Hazard Software: Program Impact Version 2.0 User's Guide"
M.E. Sorge
The Aerospace Corporation, Aerospace Report No. TOR-92(2909)-1, Los Angeles, California, November 1991
(Distribution limited to U.S. Government agencies and their contractors only)

IMPACT 2.0 is an IBM-PC-based software program used for the simulation and analysis of orbital altitude explosions and hypervelocity collisions. It is a considerably updated version of *IMPACT 1.0B*. As with version 1.0B, *IMPACT 2.0* can be hosted on an IBM-PC or compatible Model 286 or larger with at least 470 K of free memory. A hard drive of at least 10 MB is also needed. The PC to be used should be equipped with either a 5-1/4-in or a 3-1/2-in disk. Also, a math-coprocessor and a Hercules, EGA, or VGA graphics board are needed. About 2 MB of free memory on the hard disk should be sufficient in most cases. *IMPACT 2.0* actually is a collection of subprograms whose interactions and applications are automatically coordinated by an overseeing shell program that offers a main menu which displays all of the options available to the user. These options include the execution of the various subprograms in *IMPACT*. In addition to the fragmentation model, *IMPACT 2.0* contains subprograms *LIFETIME* and *FOOTPRINT* which estimate how long debris fragments from a given breakup event remain on-orbit and the terrestrial locations of those that re-enter. *IMPACT 2.0* also generates an input file for program *DEBRIS*, an orbital collision hazard analysis program. Program *DEBRIS* calculated the collision hazard posed to orbiting satellites by orbital fragmentation event produced debris. This paper documents the requirements and procedures needed in order to run *IMPACT 2.0* and view the results.

"Space Debris Hazard Software: Program Impact Version 3.0 User's Guide"
M.E. Sorge and C.G. Johnson
The Aerospace Corporation, Aerospace Report No. TOR-93(3076)-3, Los Angeles, California, August 1993
(Distribution limited to U.S. Government agencies and their contractors only)

IMPACT 3.0 is an IBM-PC-based software program used for the simulation and analysis of orbital altitude explosions and hypervelocity collisions. It is the latest version of *IMPACT*, which includes *IMPACT 1.0B* and *IMPACT 2.0* to *2.02*. As with Version 2.02, *IMPACT 3.0* can be hosted on an IBM-PC, or compatible Model 386 or larger, with at least 640 K of free RAM. A hard drive of at least 10 megabytes (MB) also is needed. The PC to be used should be equipped with a 3-1/2-inch disk drive in order for the program to be transferred to the computer. Also, a math-coprocessor and an EGA or VGA graphics board are needed. About 2 MB of free memory on the hard disk should be sufficient in most cases. *IMPACT 3.0* is a collection of subprograms whose interactions and applications are automatically coordinated by an overseeing shell program that offers a main menu which displays all of the options available to the user. These options include the execution of the various subprograms in *IMPACT*. In addition to the fragmentation model, *IMPACT 3.0* contains subprograms *LIFETIME* and *FOOTPRINT* which estimate how long debris fragments from a given breakup event remain on-orbit and the terrestrial locations of those that re-enter. *IMPACT 3.0* also generates an input file for program *DEBRIS 3.0*, an orbital collision hazard analysis program. Program *DEBRIS* calculates the collision hazard posed to orbiting satellites from orbital fragmentation event produced debris. This paper documents the requirements and procedures needed in order to run *IMPACT 3.0* and view the results.

"The Average Cross-Sectional Area of Solids as a Measure of Mechanical Disorder"

A. Tan, F.A. Allahdadi, and S.R. Maethner

American Association of Physics Teachers Announcer, Vol. 23, December 1993

The existence of fundamental principles in the fragmentation of solids similar to the entropy principles in heat flow is discussed. The fragmentation of solids is identified as an irreversible process and the average cross-sectional area is recognized as a measure of mechanical disorder. It is found that ideally the average cross-sectional area of a solid may remain constant (if it was an ideal flat plate) or increase (in all other cases), but cannot decrease. For actual fragmentation processes, however, the average cross-sectional area must always increase. These principles are verified in actual documented cases of satellite breakups, both in space and in the laboratories.

"Satellite Fragmentation: Explosion vs. Collision"

A. Tan, F.A. Allahdadi, S.R. Maethner, and J.E. Winter

Orbital Debris Monitor, Vol. 6, No. 2, April 1993

Since the breakup of Transit 4A rocket in 1961, over one hundred artificial earth satellites have fragmented in orbit, creating a large amount of hazardous material in space. Most were broken up by explosion (whether inadvertent or deliberate) and some are known or alleged to have been broken up by hypervelocity impact as part of anti-satellite (ASAT) testing. Yet others are classified as belonging to the unknown category. To determine the cause of a fragmentation event in space retrospectively from ground-based observations remains a lingering problem for space debris researchers and strategic planners alike. Determining the probable cause of fragmentation remains handicapped at the present time. The major difficulty is the inability of the tracking system to observe small particles (smaller than about 10 cm in diameter). For it is in the mass distributions of these small particles that the major difference between the explosional and collisional signatures lie. This article examines the physical processes of fragmentation and debris generation associated with explosions and collisions.

"Determining the Effects of Space Debris Impact on Spacecraft Structures"

W. Tedeschi, J. Connell, D. Mcknight, A.E. Reinhardt, F.A. Allahdadi, R. Hunt, and D. Hogg

Acta Astronautics, Vol. 26, No. 7, March 1992

The collision hazard to space systems from trackable orbital debris has doubled over the last 15 years in some regions of low Earth orbit. Yet the hazard from nontrackable debris may be even more severe in some Earth orbits. Thousands of orbiting objects too small to be tracked reliably may damage or destroy space hardware via hypervelocity collision, resulting in mission degradation or termination and generated debris. An understanding of the modes by which a small impactor collides and interacts with a massive complex structure is required to (1) accurately determine the present debris environment, (2) quantify the operational lifetime of satellites, and (3) predict the future environment. The Defense Nuclear Agency has initiated the DoD Spacecraft Breakup Modeling Program to improve the accuracy and usefulness of satellite breakup models, with an emphasis on collision-induced events. The breakup development effort is being conducted in parallel with an experimental hypervelocity impact (HVI) test program to produce accurate data required to develop and validate the breakup models. Current results from the breakup modeling effort are presented and discussed, along with data from the associated HVI impact test program.

"Influence of Plasticity Models Upon the Outcome of Simulated Hypervelocity Impacts"

J. Thomas

Joint AIRAPT/APS Conference, Proceedings, Colorado Springs, Colorado, 28 June - 2 July 1993

This paper describes the results of numerical simulations of aluminum impacts which were performed with the CTH hydrocode to determine the effect of different plasticity formulations upon the final perforation size in the targets. The targets were 1 mm and 5 mm thick plates and the projectiles were represented as 2024 aluminum alloy. The hydrocode simulations were run in a two-dimensional cylindrical geometry. Normal impacts at velocities between 5 and 15 km/s were simulated. Three isotropic yield stress models were explored in the simulations: an elastic-perfectly plastic model and the Johnson-Cook and Steinburg-Guinan-Lund viscoplastic models. The fracture behavior was modeled by a simple tensile pressure criterion. The simulations show that using the three strength models resulted in only minor differences in the final perforation diameter. The simulation results were used to construct an equation to predict the final hole size resulting from impacts on thin targets.

"Assessment of the NASA EVOLVE Long-Term Orbital Debris Evolution Model"

K.W. Yates and F. Jonas

Phillips Laboratory Technical Report, PL-TR-92-1030, to be published

The *EVOLVE* long-term orbital debris evolution model developed for the NASA Johnson Space Center by Lockheed Engineering and Sciences Company and Systems Planning Corporation is described and evaluated in detail. This computer model calculates the low earth orbit (LEO) debris spatial number density or flux environment as a function of fragment size, altitude, and time. Launched intact objects, introduced from detailed manifest databases, are time-evolved with an analytical orbit propagator. Debris clouds, formed from the application of cloud formation algorithm and breakup model, are time-evolved using a derived phenomenological function. This report describes the overall computer model (e.g., its deterministic and stochastic modes of calculation) and examines the individual submodels used to quantify the debris population in LEO. Model results are compared to observed debris data. Specific recommendations and possible model improvements are cited. Also presented is a sample satellite constellation hazard assessment using *EVOLVE.*

"Assessment of the NASA Orbital Debris Engineering Model"

K.W. Yates and F. Jonas

Phillips Laboratory Technical Report, PL-TR-92-1032, to be published

This report presents an assessment of the orbital-debris engineering model to predict near and long-term orbital-debris environment on spacecraft in low earth orbit. The model predicts debris flux environment, collision-velocity impact distribution and direction, and debris particle mass. The empirically based model is a curve fit to measured data and incorporates results derived from the NASA *EVOLVE* code. The data base includes U.S. Space Command orbital element sets, Aricebo and Goldstone radar observations, MIT/Lincoln Laboratory Experimental Test Site, ground-based electro-optical deep space surveillance optical data, and solar maximum mission surface impact data. The model is most sensitive to the small-debris particles and becomes undefined as the particle size approaches zero. The model is least sensitive to changes in orbital altitude. The model predicts essentially constant flux >1000 km and does not reproduce measured data at these altitudes. The uncertainty is shown to be a factor of 2 to 4 for an altitude of 500 $\pm$ 200 km (all particle sizes) and for sizes >10 cm (for all altitudes), and at least an order of magnitude for all other sizes and altitudes. The collision-velocity, impact distribution, and direction and particle mass expressions represent extremely gross approximations of the environment. On the basis of the results of the analysis, it is recommended the model's use be restricted to altitudes <1000 km and debris sizes from 10^3 to 10^{-4} cm through the year 2010.

"Orbital Debris Environment Predictions Based on a Long-Term Orbital Debris Evolution Model"

K.W. Yates and F. Jonas

44th Congress of the International Astronautical Federation, IAA.6.3-93-745, 16 October 1993

This paper describes the adaptation and application of a long-term debris evolution model called *EVOLVE-D* capable of predicting the current and future debris population in low earth orbit. It was developed for the Air Force Phillips Laboratory to be the long-term model component of the Debris Analysis Workstation for use in population and debris hazard analysis. It is adapted from the *EVOLVE* model originally developed for NASA Johnson Space Center, but has been equipped with several added capabilities and features. Among these are the addition of the *IMPACT 3.0* debris cloud breakup model, the incorporation of a debris cloud model to dynamically generate and propagate limited sets of fragments, and the addition of user friendly input menus and screen plotting graphics features. This paper details these added capabilities of the *EVOLVE-D* model and then presents some debris population estimated of current environments using this modeling tool.

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